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A Traffic-Actuated Electromechanical Road Harvester for Generating Electricity from Passing Vehicles: Design Concept, Analytical Energy Model and Comparison with Published Roadway Harvesters

Ramozonova Fotima Yorboyevna
PhD student at Bukhara State University
ramazonovafotima71@gmail.com

Abstract

Road traffic dissipates part of the vehicle energy in pavement deformation and braking, yet road-side electrical loads are still supplied by cables or batteries. This paper describes an electromechanical road energy harvester protected by the Uzbek invention patent No. IAP 8475 (priority date 13 December 2025). The wheel load of a passing vehicle depresses a spring-returned top plate, and a rack-and-pinion, an overrunning clutch and a speed-increasing gear train drive a flywheel-coupled permanent-magnet synchronous generator whose output is rectified and stored. A closed-form estimate of the recovered electrical energy, $E_{el} = \eta_{tot} mgs$, is derived and evaluated for three vehicle classes and plate strokes of 10–20 mm. With an assumed overall conversion efficiency of 0.52 and a 15 mm stroke, the model gives about 115 J per 1.5 t passenger car, 268 J per 3.5 t light commercial vehicle and 1.53 kJ per 20 t truck. For a mixed flow of 5000 vehicles per day, the recovered energy is about 0.22 kWh/day, and about 11 100 vehicles per day are needed to supply one 40 W LED lamp for 12 h. The energy taken from a vehicle equals $2gs/v^2$ of its kinetic energy, about 1% at 20 km/h. The model is compared with 18 published studies of piezoelectric, electromagnetic, triboelectric, thermoelectric, wind and vehicle-mounted harvesters retrieved from PubMed. Displacement-type electromechanical harvesting recovers several orders of magnitude more energy per vehicle than pavement-embedded piezoelectric devices, but it takes this energy from the vehicle and is therefore suited to sites where traffic must slow down anyway.

Keywords: Electromagnetic generator, energy harvesting, rack-and-pinion mechanism, road infrastructure, speed bump, traffic-induced energy.

I. Introduction

Road networks carry a growing number of electrical loads: street and crossing lighting, illuminated signs, traffic counters, weigh-in-motion stations and pavement condition sensors. Zheng *et al.* [1] identify the power supply of distributed sensor networks as the main bottleneck of intelligent roads, because cabled supply is costly to extend and batteries have short service lives and high maintenance costs; the same review concludes that current road micro-energy harvesting technologies cannot yet meet the demand of large-scale sensor networks [1]. Harvesting part of the mechanical energy that vehicles already deliver to the road is one way to supply such loads locally.

The conversion principles available for this purpose (photovoltaic, electromagnetic, piezoelectric, triboelectric, thermoelectric and others) were surveyed by Bai *et al.* [2]. The following subsections review how these principles have been applied to road traffic and identify the gap addressed here.

A. Road-Embedded Harvesters

Piezoelectric transducers embedded in the pavement have received the most study. Li *et al.* [3] developed a device made of stacked piezoelectric units that delivered 84.3 mW at a 10 kN, 10 Hz load, kept its electrical properties after 100 000 load cycles and produced an open-circuit voltage of 190 V under a real tire load; traffic parameters could also be extracted from its voltage waveform. Yang *et al.* [4] studied how the connection mode, the number of stack layers, the height-to-area ratio and the number of units affect the output of stack harvesters under accelerated pavement testing. Finite-element studies showed that the voltage depends on the embedding depth and on the horizontal distance between the tire and the transducer [5], and that distributing more, smaller piezoelectric units in a 30 cm × 30 cm harvester increases the energy but also the stress concentration near the edges [6]. Vázquez-Rodríguez *et al.* [7] built a programmable traffic-simulating test bench whose models predicted the harvested power with a relative error below

3%, and compared lead-containing and lead-free piezoceramics. Flexible composite films placed at the roadside have been tested under motorcycles and bicycles [8].

Other road-embedded principles have lower outputs. A thermoelectric cement composite reinforced with carbon nanotubes and $Bi_{0.5}Sb_{1.5}Te_3$ improved its figure of merit by a factor of 842 but still generated only 0.002 µW at a temperature difference of 19.1 K [9]. Triboelectric nanogenerators have been reviewed for vehicle vibration, wheel–road and on-board applications, where they serve mainly as self-powered sensors [10].

A common limitation of pavement-embedded harvesters is that they operate at the small deflections of a stiff pavement, so the energy recovered per vehicle is small. In a field installation with 16 piezoelectric cantilevers, Heller *et al.* [11] measured a peak power of 55.6 µW per transducer and estimated a generation capacity of about 50 mWh per month for a traffic volume of 1500 vehicles per day. Dipon *et al.* [12] reported that only 0.25% of the mechanical power of passing vehicles reached their stacked piezoelectric harvester. Electromagnetic harvesters deliver higher power but have been described as bulky and as requiring large input displacements [13]; Mou *et al.* [13] addressed this with a pavement harvester that uses frequency up-conversion and unidirectional rotation and reached 171.14 mW in laboratory tests.

B. Vehicle-Mounted and Road-Side Harvesters

A second line of work recovers energy on board the vehicle, mainly through regenerative shock absorbers. A Monte Carlo study of a quarter-car model found that the harvestable power bandwidth was most sensitive to the excitation, the damping rate and the tire properties, and hardly changed with the body and wheel masses or the spring stiffness [14]. Reyes-Avendaño *et al.* [15] showed that a ball-screw regenerative damper can replicate a passive damper curve only above a minimum damper velocity, and noted that no commercial energy-harvesting shock absorber existed at the time of their study. In simulation, an optimal linear-quadratic control law increased the harvested energy by 37.3% and 27.8% compared with two reference strategies [16]. Piezoelectric patches on the tire inner liner generated voltages that increased with patch size, speed and normal load [17]. Road-side wind is a further source: a hybrid turbine that starts at low wind speed has been developed for urban self-powered sensing [18], and a triboelectric wind harvester has been used to power a traffic light system [19].

C. Research Gap and Contributions

Among the records retrieved for this study (Section II-D), none described an electromechanical harvester with a stroke of the order of 10 mm installed at a traffic-calming location, and the reported outputs of road harvesters are given in units that are difficult to compare (peak power, open-circuit voltage, energy per month or efficiency). This paper addresses both points. Its contributions are: (i) a description of the traffic-actuated electromechanical harvester of patent IAP 8475 [20]; (ii) a closed-form model of the electrical energy recovered per vehicle and per day, with explicit assumptions and a sensitivity range; (iii) a comparison of the model with published road, wind and vehicle-mounted harvesters on a common per-vehicle basis; and (iv) siting and design implications. Section II describes the device, the model and the literature analysis, Section III reports the results, Section IV discusses them and Section V concludes the paper.

II. Materials and Methods

A. Device Description

The harvester is a steel housing installed flush with the road surface across the traffic lane, so that both wheels of each axle load it (Fig. 1). A top plate with a profiled upper surface protrudes above the road by the working stroke s and is guided vertically; return springs lift it back after each axle has passed. A toothed rack fixed to the underside of the plate engages a pinion of pitch radius r_p on the input shaft. An overrunning (one-way) clutch transmits torque only during the downward stroke, so the shaft always turns in one direction, and a gear train with speed ratio i drives a flywheel and a three-phase permanent-magnet synchronous generator (PMSG). During the return stroke, the clutch disengages, and the flywheel keeps the generator turning between axles. The generator output is rectified, conditioned by a DC–DC converter that tracks the maximum power point and stored in a battery, which supplies roadside loads such as LED lighting, illuminated signs and sensors.

The combination of unidirectional rotation and frequency up-conversion was chosen because it allowed a small electromagnetic pavement harvester to convert a short reciprocating input into continuous rotation with high output power in the tests of Mou *et al.* [13]. The device described here applies the same principle at a stroke of the order of 10 mm, which is comparable with the height of a low-speed bump, instead of the few millimetres of pavement deflection.

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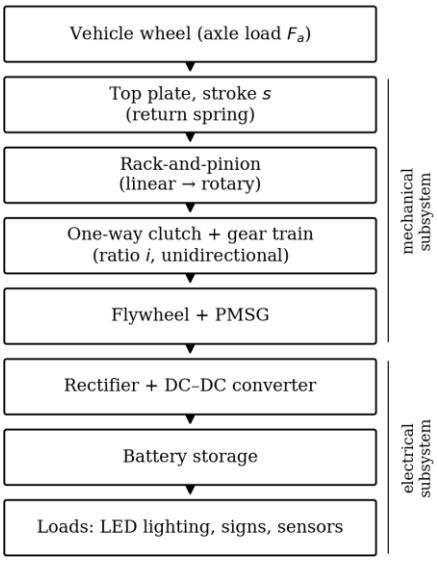

Fig. 1. Energy conversion chain of the traffic-actuated electromechanical harvester. PMSG: permanent-magnet synchronous generator.

B. Analytical Energy Model

When an axle with static load F_a rolls onto the plate, the plate moves down by s against the reaction force $F_r(x)$ of the springs and of the generator reflected through the gear train. Because the plate cannot support more than the axle load, the mechanical work delivered per axle is bound by

$$W_a = \int_0^s F_r(x)\,dx \le F_a s. \tag{1}$$

Summing over the axles of a vehicle and using the fact that the static axle loads add up to the vehicle weight gives, for a vehicle of mass m,

$$W_v \le \Sigma_k F_{a,k} s = mgs. \tag{2}$$

The bound mgs have a simple interpretation: it equals the change in potential energy of the vehicle if its whole weight were lowered by the stroke s. In practice, the vehicle does not lose height permanently; the work is supplied from its kinetic energy as the wheels roll over the plate edge, which is why the loss is expressed as a share of kinetic energy in (6) below.

The recovered electrical energy per vehicle is then

$$E_{el} = \eta_{tot} mgs,\ \eta_{tot} = \lambda \eta_m \eta_g \eta_c, \tag{3}$$

where λ is the fraction of the bound (2) that becomes shaft work (it accounts for spring preload, plate inertia and incomplete strokes), and η_m, η_g and η_c are the efficiencies of the mechanical transmission, the generator and the power electronics. For a traffic flow of N vehicles per day in which class j has share p_j and mass m_j, the daily energy is

$$E_d = N \eta_{tot} gs\ \Sigma_j\ p_j m_j. \tag{4}$$

The kinematics of one stroke follow from the plate length L_p along the road and the vehicle speed v. The stroke time and the mean generator speed during the stroke are

$$t_p \approx L_p / v,\ \omega_g \approx is/(r_p t_p), \tag{5}$$

and the fraction of the vehicle kinetic energy that the harvester removes is

$$\xi = mgs/(\tfrac{1}{2} m v^2) = 2gs/v^2, \tag{6}$$

which does not depend on the vehicle mass. The parameter values are listed in Table I. The efficiencies are design assumptions taken as typical of gear transmissions, small PMSGs and switching converters; they were not measured on the device, and the daily energy is therefore also reported for η_{tot} between 0.30 and 0.60. The model uses static axle loads and ignores dynamic load amplification, tire enveloping and lateral wheel wander. A one-at-a-time sensitivity analysis varied each parameter between the limits given in Section III-G while keeping the others at their baseline values.

Table I. Model Parameters

Parameter	Symbol	Value
Plate stroke	s	10, 15, 20 mm
Plate length along the road	L_p	0.30 m
Pinion pitch radius	r_p	10 mm
Gear train speed ratio	i	20
Stroke utilisation factor	λ	0.80
Transmission efficiency	η_m	0.85
Generator efficiency	η_g	0.85
Power electronics efficiency	η_c	0.90
Overall efficiency (baseline)	η_{tot}	0.52
Vehicle speed over the plate	v	20 km/h
Traffic mix: car / light commercial / truck	p_j	0.90 / 0.08 / 0.02
Class masses	m_j	1.5 / 3.5 / 20 t

C. Transmission, Flywheel and Storage Sizing

The mean reaction force on the rack during a stroke is λF_a. The resulting pinion torque and the torque at the generator shaft are

$$T_p = \lambda F_a r_p,\ T_g = \eta_m T_p / i. \tag{7}$$

The flywheel must absorb the shaft work of one axle stroke, $W_{sh} = \lambda \eta_m F_a s$, while its speed falls from ω_{max} to $k\omega_{max}$ between axles. Its moment of inertia must therefore satisfy

$$J_f \geq 2W_{sh}/[\omega_{max}^2(1 - k^2)]. \tag{8}$$

A battery that supplies a daily load energy E_L at nominal voltage U with an allowed depth of discharge D needs a capacity

$$C = E_L/(UD). \tag{9}$$

For the sizing example, ω_{max} was taken as the mean generator speed from (5), k = 0.8, E_L = 0.48 kWh (one 40 W LED lamp for 12 h), U = 12.8 V (four lithium iron cells in series) and D = 0.8.

D. Literature Analysis

Published harvesters were identified in PubMed in September 2026 with two structured queries: (a) road, pavement, roadway, traffic, vehicle, speed bump or deceleration in the title combined with energy harvesting, harvester or harvesters in the title; and (b) pavement, asphalt or traffic load in the title or abstract combined with piezoelectric, electromagnetic, triboelectric or energy harvesting in the title. The queries returned 33 unique records. A similarity search seeded with the electromagnetic pavement harvester of [13] added 15 candidates. Titles and abstracts of the 48 records were screened. Studies were retained if they reported measured or simulated results for a road, traffic or vehicle-mounted harvester, or for a transducer principle directly applicable to one; records on electromagnetic shielding, ground-penetrating radar, asphalt heating and weigh-in-motion sensing without energy output were excluded. Eighteen primary studies were retained, and three reviews [1], [2], [10] were used for background. For each primary study, the transduction principle, the placement, the excitation, the reported output with its test conditions and whether the device was tested under real traffic were extracted as reported by the authors.

III. Results

A. Energy per Vehicle

Table II and Fig. 2 give the electrical energy per vehicle from (3). Energy grows linearly with vehicle mass and stroke. At the baseline stroke of 15 mm a passenger car yields 114.8 J, a light commercial vehicle 267.9 J and a heavy truck 1530.9 J. Reducing the stroke to 10 mm lowers these values by one third, to 76.5 J, 178.6 J and 1020.6 J; a 20 mm stroke raises them to 153.1 J, 357.2 J and 2041.3 J. Because heavy vehicles carry most of the load, the 2% truck share contributes about 20% of the mean energy per vehicle in the baseline traffic mix.

Table II. Electrical Energy per Vehicle (J) at Overall Efficiency 0.52

Vehicle class	s = 10 mm	s = 15 mm	s = 20 mm
Passenger car, 1.5 t	76.5	114.8	153.1
Light commercial, 3.5 t	178.6	267.9	357.2
Heavy truck, 20 t	1020.6	1530.9	2041.3
Traffic-mix mean	103.6	155.4	207.2

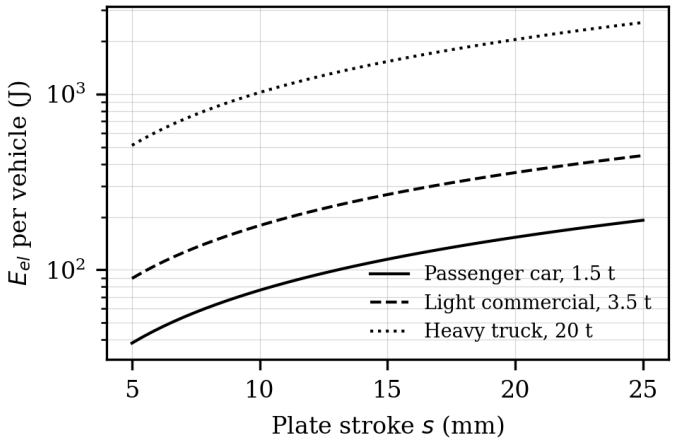

Fig. 2. Electrical energy recovered per vehicle as a function of plate stroke for three vehicle classes (baseline η_{tot} = 0.52; logarithmic scale).

B. Stroke Kinematics and Power

At 20 km/h and a plate length of 0.30 m, (5) gives a stroke time of about 0.054 s. With r_p = 10 mm, the pinion turns through 1.5 rad per 15 mm stroke, and with i = 20 the generator completes about 4.8 revolutions per axle, at a mean speed of about 555 rad/s (5300 r/min) during the stroke. The mean electrical power during the stroke of one passenger-car axle is about 1.06 kW. The harvester therefore receives short pulses of the order of a kilowatt lasting ten milliseconds, separated by idle intervals that depend on traffic headway.

C. Daily Energy

With the traffic mix of Table I, the mean energy per vehicle is 155.4 J. Fig. 3 shows the daily energy from (4). At 5000 vehicles per day the harvester delivers about 0.22 kWh/day (0.12–0.25 kWh/day across the efficiency range); at 10 000 vehicles per day, 0.43 kWh/day; and at 20 000 vehicles per day, 0.86 kWh/day. A 40 W LED lamp operated for 12 h consumes 0.48 kWh, which requires about 11 100 vehicles per day at the baseline efficiency and a stroke of 15 mm.

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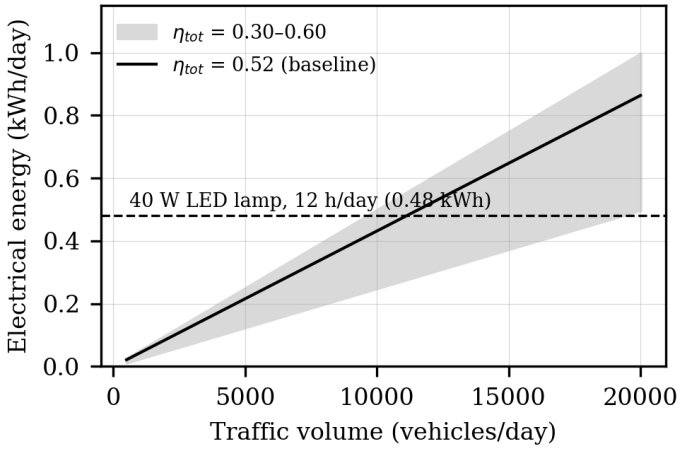

Fig. 3. Daily electrical energy versus traffic volume for the mix of Table I and s = 15 mm. The shaded band covers η_{tot} = 0.30–0.60; the dashed line is the daily consumption of one 40 W LED lamp operated 12 h.

D. Energy Taken from the Vehicle

From (6), a 15 mm stroke removes 3.8% of the kinetic energy of a vehicle at 10 km/h, 0.95% at 20 km/h and 0.42% at 30 km/h, for any vehicle mass. For a 1.5 t car at 20 km/h this is 221 J of mechanical work out of a kinetic energy of 23.1 kJ.

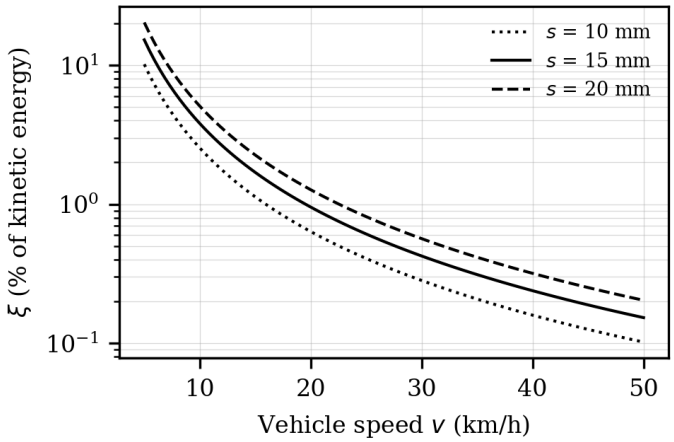

Fig. 4. Share of vehicle kinetic energy removed by one pass over the harvester, from (6), for three plate strokes (logarithmic scale). The share is independent of vehicle mass.

Fig. 4 shows that the share falls with the square of speed. At 40 km/h a 15 mm stroke removes 0.24% of the kinetic energy, but a vehicle crossing a raised plate at that speed would experience a vertical jolt; the useful operating range is therefore the low-speed range typical of traffic-calming locations.

E. Component Loads and Storage

From (7), a passenger-car axle produces a pinion torque of 58.9 N·m and a generator shaft torque of 2.50 N·m. A 3.5 t light commercial vehicle gives 137.3 N·m and 5.84 N·m, and a 20 t truck axle gives 523.2 N·m and 22.24 N·m. The shaft work per car axle at s = 15 mm is 75.0 J; with ω_{max} = 555 rad/s and k = 0.8, (8) gives a flywheel inertia of 1.35×10^{-3} kg·m^2, which a steel disc of 0.06 m radius and about 0.75 kg provides. From (9), storing one lamp-night of 0.48 kWh requires a battery of about 47 A·h at 12.8 V.

F. Site Scenarios

Table IV applies (4) to five traffic volumes representing typical installation sites. The annual energy ranges from 15.8 kWh at 1000 vehicles per day to 315.1 kWh at 20 000 vehicles per day, equivalent to between 33 and 656 nights of operation of one 40 W LED lamp.

Table IV. Energy Yield for Representative Traffic Volumes (s = 15 mm, Baseline Efficiency)

Traffic (veh/day)	kWh/day	kWh/year	Lamp-nights/year
1000	0.043	15.8	33
3000	0.129	47.3	98
5000	0.216	78.8	164
10 000	0.432	157.5	328
20 000	0.863	315.1	656

The lamp-night figures assume that all recovered energy reaches the lamp after storage; battery round-trip losses, which were not included in η_{tot}, would reduce them.

G. Sensitivity Analysis

Fig. 5 shows the one-at-a-time sensitivity of the daily energy at 5000 vehicles per day, whose baseline is 0.216 kWh/day. The plate stroke has the largest effect (0.144–0.288 kWh/day for 10–20 mm), followed by the truck share (0.176 kWh/day with no trucks and 0.275 kWh/day with 5% trucks, the car share being reduced accordingly) and the utilisation factor λ (0.162–0.243 kWh/day for 0.60–0.90). Among the efficiencies, the generator (0.178–0.234 kWh/day for 0.70–0.92) matters more than the transmission (0.190–0.241 kWh/day for 0.75–0.95) and the power electronics (0.192–0.228 kWh/day for 0.80–0.95).

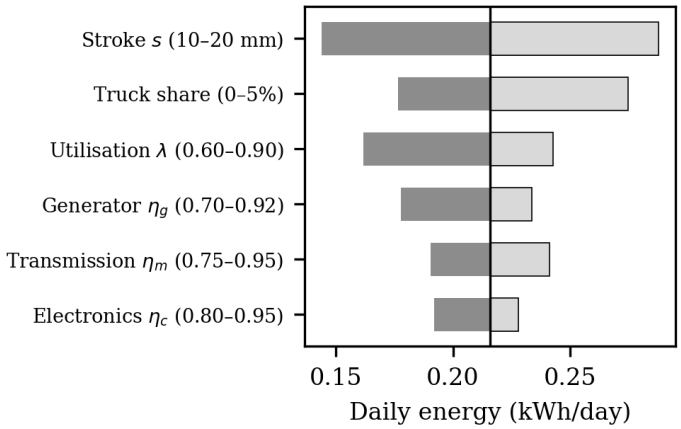

Fig. 5. One-at-a-time sensitivity of the daily energy at 5000 vehicles per day. Dark bars: parameter at its lower limit; light bars: upper limit. The vertical line is the baseline (0.216 kWh/day).

H. Comparison with Published Harvesters

Table III lists the outputs reported in retained studies that provide quantitative device output. Pavement-embedded piezoelectric devices reported outputs from microwatts per transducer in the field [11] to 84.3 mW for a stack device under a 10 kN, 10 Hz laboratory load [3]. The field monthly figure of [11] corresponds to about 180 J per month, or about 0.004 J per vehicle at 1500 vehicles per day, against 114.8 J per passenger car from the present model. Electromagnetic devices reached 171.14 mW [13] and 182 mW [21] in laboratory tests, and in a hybrid, harvester tested under the same excitation, the electromagnetic unit delivered 87.1 mW, compared with 63 µW for the triboelectric unit [22]. The thermoelectric cement composite of [9] produced 0.002 µW.

Table III. Reported Outputs of Road, Wind and Vehicle Harvesters

Device, placement [ref.]	Reported output (conditions)	Field test
Piezoelectric stack, pavement [3]	84.3 mW (10 kN, 10 Hz, 275 kΩ); 190 V open circuit under tire load	Yes
Piezoelectric cantilever array, pavement [11]	55.6 µW peak per transducer; ≈50 mWh/month for 16 units at 1500 veh/day	Yes
Stacked PZT + TEG, road [12]	0.25% of vehicle mechanical power reached harvester; PZT efficiency 37%	Yes
Flexible piezo composite, roadside [8]	≈16 V peak-to-peak under a motorcycle	Yes

Device, placement [ref.]	Reported output (conditions)	Field test
Thermoelectric cement [9]	0.002 μW at ΔT = 19.1 K	No
Electromagnetic, up-frequency, pavement [13]	171.14 mW (9 Hz, 3.0 mm); no voltage decay after 100 000 cycles	No
Piezo–electromagnetic, rotary [21]	182 mW at 120 r/min	No
Piezo/EM/triboelectric hybrid [22]	EM 87.1 mW; piezo 26.17 mW; tribo 63 μW (4 Hz)	No
Tribo–EM wind turbine, urban [18]	Start-up at 1.2 m/s wind speed	No
PVDF patches on tire [17]	Voltage rose with patch size, speed and load	Yes
Regenerative suspension control [16]	+37.3% energy vs. regenerative damper (simulation)	No
This work, displacement EM	114.8 J per car (model, s = 15 mm)	No

IV. Discussion

A. Energy Yield Relative to Pavement Harvesters

The main result is that a displacement-type electromechanical harvester with a stroke of 10–20 mm can recover of the order of 10^2 J per passenger car, several orders of magnitude more than the per-vehicle yield implied by the field data of pavement-embedded piezoelectric devices (about 0.004 J per vehicle derived from [11]). The difference follows from (2): the available work is proportional to the stroke, and a plate that moves by 15 mm offers far more work than a pavement that deflects by fractions of a millimetre. The low vehicle-to-harvester fraction of 0.25% measured by Dipon *et al.* [12] has the same origin. Model and measurements are, however, not strictly comparable, because Table III mixes field and laboratory results and the present values have not yet been measured on a prototype.

B. Choice of Conversion Principle

The choice of electromagnetic conversion agrees with the published comparisons. Under identical excitation, the electromagnetic unit of the hybrid harvester in [22] produced more than 1000 times the power of the triboelectric unit, and electromagnetic pavement and rotary harvesters reached 171–182 mW in the laboratory [13], [21]. Triboelectric and polymer piezoelectric devices appear better suited to self-powered sensing, such as traffic and tyre–road contact monitoring [10], [17], than to supplying lighting loads.

C. Energy Cost to the Vehicle and Siting

The recovered energy is not free. According to (6), the harvester removes about 1% of the kinetic energy of a vehicle at 20 km/h, and on a free-flowing road this energy would be replaced by fuel or traction battery energy. The device is therefore appropriate where vehicles must slowdown in any case and where the corresponding energy would otherwise be dissipated in brakes: pedestrian crossings near schools, entrances to parking areas, toll and checkpoint approaches, and industrial or residential access roads where speed bumps are already installed. At such sites, the plate can replace a conventional speed bump. This sitting argument is qualitative; a net energy balance at a specific site would require measured speed profiles with and without the device.

D. Design Requirements

The kinematic results set the main design requirements. Pulses of about 1 kW lasting about 50 ms require a generator and converter rated for the peak rather than the mean power, and a flywheel or electrical buffer to spread the energy over the idle intervals. The number of load cycles is high: at 5000 vehicles per day with two axles each, the plate completes about 10 000 strokes per day, or about 3.7 million per year. The 100 000-cycle endurance tests reported for an electromagnetic [13] and a piezoelectric [3] pavement harvester correspond to about ten days of such traffic, so gear, clutch and spring fatigue over millions of cycles is the main durability question for the proposed device.

The torque results show that the two design limits are set by different vehicles. Heavy trucks set the strength requirements: the overrunning clutch, the pinion and the rack must carry about 520 N·m at the pinion, nine times the passenger-car value. Passenger cars, which make up most of the traffic, set the efficiency requirements: the generator works most of the time at about 2.5 N·m, and its efficiency at this partial load, not at rated load, determines η_g. A torque limiter or a slipping clutch that caps the transmitted torque would allow a smaller gear train while sacrificing part of the truck energy, which in the baseline mix is about 20% of the total. The flywheel required by (8) is small, about 0.75 kg, so the buffering between axles adds little mass or cost; the battery, of the order of 50 A·h for one lamp-night, is the larger storage component.

Because the raised plate acts as a speed bump, its profile, marking, and installation must also satisfy the road authority rules for traffic-calming devices. The stroke is a compromise between energy, which grows linearly with s according to (3), and driver comfort and vehicle clearance, which limit the height of the plate above the road.

E. Relation to Other Energy Sources

On-vehicle harvesting through regenerative suspensions [14]–[16] recovers energy that would otherwise be dissipated in dampers, but the energy then serves the vehicle, not the road-side loads considered here. Roadside wind harvesters [18], [19] use a different source and could be combined with the proposed device in a hybrid supply for lighting or signals at the same site.

Table V summarises the approaches discussed in this section by the scale of their output, the energy they take from the vehicle and the application for which the evidence supports them.

Table V. Qualitative Comparison of Approaches for Road-Side Loads

Approach [refs.]	Output scale	Energy taken from vehicle	Supported use
Pavement piezoelectric [3], [11], [12]	µW–mW; ≈4 mJ per vehicle in field [11]	Negligible	Self-powered traffic sensing
Displacement electromagnetic (this work)	≈10^2 J per car (model)	≈1% of kinetic energy at 20 km/h	Lighting and signs at calming sites
Triboelectric, polymer piezo [10], [22], [17]	µW level per unit [22]	Negligible	Sensing, monitoring
Thermoelectric pavement [9]	0.002 µW per sample [9]	None	Not yet practical
Roadside wind [18], [19]	Depending on wind speed	None	Lights, sensors
Regenerative suspension [14]–[16]	on board (simulated gains [16])	Returned to vehicle	Vehicle electrical system

F. Limitations and Validation Protocol

The study has four limitations. First, the efficiencies in Table I are assumptions; the sensitivity band of Fig. 3 shows their effect, but the actual η_{tot} must be measured. Second, the model uses static loads and neglects dynamic amplification, speed-dependent generator losses and lateral wheel wander, which reduces the share of wheels that fully load a plate narrower than the lane. Third, the literature search covered PubMed only, which indexes part of the engineering literature; databases such as IEEE Xplore and Scopus were not searched. Fourth, no prototype results are yet available.

A validation protocol follows directly from the model. On a servo-hydraulic load frame, the plate should be driven through strokes of 10, 15 and 20 mm under peak loads of about 7, 17 and 65 kN, which correspond to the axle loads of the three vehicle classes, at stroke times of 0.04–0.11 s, which correspond to 10–30 km/h over a 0.30 m plate. For each case the electrical energy delivered to a set of resistive loads and to the battery should be integrated over the stroke and divided by the measured mechanical work to obtain η_{tot} and λ. A fatigue test of at least several million strokes would then check the transmission and the clutch. Finally, a field installation at a traffic-calming site with an automatic vehicle counter and speed measurement would allow the measured daily energy to be compared with (4), and the change in approach speed to be recorded.

V. Conclusion

A traffic-actuated electromechanical road harvester (Patent IAP 8475) was described, and a closed-form model of the energy it recovers, $E_{el} = \eta_{tot} mgs$, was derived. With an assumed overall efficiency of 0.52 and a 15 mm stroke, the model predicts about 115 J per passenger car, 268 J per light commercial vehicle and 1.53 kJ per heavy truck, and about 0.22 kWh/day for 5000 vehicles per day; about 11 100 vehicles per day would supply one 40 W LED lamp for 12 h. These per-vehicle values exceed those implied by field data from pavement-embedded piezoelectric harvesters by several orders of magnitude. Because the device removes about 1% of the kinetic energy of a vehicle at 20 km/h, it should be installed where traffic calming is already required. Prototype measurement of conversion efficiency and long-term fatigue testing are needed before these estimates can be confirmed.

References

[1] G. Zheng, C. Xing, L. Zhang, H. Li, T. Cheng, and Y. Tan, “Micro-energy harvesting and self-powered sensing for intelligent road: A comprehensive review,” *Research*, vol. 9, Art. no. 1171, 2026, doi: 10.34133/research.1171.

[2] Y. Bai, H. Jantunen, and J. Juuti, "Energy harvesting research: The road from single source to multisource," *Adv. Mater.*, Art. no. e1707271, 2018, doi: 10.1002/adma.201707271.

[3] C. Li *et al.*, "Development and piezoelectric properties of a stack units-based piezoelectric device for roadway application," *Sensors*, vol. 21, no. 22, Art. no. 7708, 2021, doi: 10.3390/s21227708.

[4] H. Yang, Y. Wei, W. Zhang, Y. Ai, Z. Ye, and L. Wang, "Development of piezoelectric energy harvester system through optimizing multiple structural parameters," *Sensors*, vol. 21, no. 8, Art. no. 2876, 2021, doi: 10.3390/s21082876.

[5] H. Yang, Q. Zhao, X. Guo, W. Zhang, P. Liu, and L. Wang, "Numerical analysis of signal response characteristic of piezoelectric energy harvesters embedded in pavement," *Materials*, vol. 13, no. 12, Art. no. 2770, 2020, doi: 10.3390/ma13122770.

[6] C. Du, P. Liu, H. Yang, G. Jiang, L. Wang, and M. Oeser, "Finite element modeling and performance evaluation of piezoelectric energy harvesters with various piezoelectric unit distributions," *Materials*, vol. 14, no. 6, Art. no. 1405, 2021, doi: 10.3390/ma14061405.

[7] M. Vázquez-Rodríguez, F. J. Jiménez, L. Pardo, P. Ochoa, A. M. González, and J. de Frutos, "A new prospect in road traffic energy harvesting using lead-free piezoceramics," *Materials*, vol. 12, no. 22, Art. no. 3725, 2019, doi: 10.3390/ma12223725.

[8] V. Vivekananthan, N. R. Alluri, Y. Purusothaman, A. Chandrasekhar, and S.-J. Kim, "A flexible, planar energy harvesting device for scavenging road side waste mechanical energy via the synergistic piezoelectric response of $KNaNbO_3$–$BaTiO_3$/PVDF composite films," *Nanoscale*, vol. 9, no. 39, pp. 15122–15130, 2017, doi: 10.1039/c7nr04115b.

[9] H. Zhou *et al.*, "Enhanced thermoelectric performances of CNTs-reinforced cement composites with $Bi_{0.5}Sb_{1.5}Te_3$ for pavement energy harvesting," *Nanomaterials*, vol. 12, no. 21, Art. no. 3883, 2022, doi: 10.3390/nano12213883.

[10] C. Zhu, Y. Ren, Z. Xi, and H. Du, "Triboelectric nanogenerators for vehicle energy harvesting and intelligent sensing," *Micromachines*, vol. 17, no. 8, Art. no. 975, 2026, doi: 10.3390/mi17080975.

[11] L. F. Heller, L. A. T. Brito, M. A. J. Coelho, V. Brusamarello, and W. P. Nuñez, "Development of a pavement-embedded piezoelectric harvester in a real traffic environment," *Sensors*, vol. 23, no. 9, Art. no. 4238, 2023, doi: 10.3390/s23094238.

[12] W. Dipon, B. Gamboa, M. Estrada, W. P. Flynn, R. Guo, and A. Bhalla, "Self-sustainable IoT-based remote sensing powered by energy harvesting using stacked piezoelectric transducer and thermoelectric generator," *Micromachines*, vol. 14, no. 7, Art. no. 1428, 2023, doi: 10.3390/mi14071428.

[13] K. Mou, X. Ji, X. Li, H. Zhou, Y. Wu, and Y. Fang, "A green electromagnetic energy harvester with up-frequency and unidirectional rotation for smart pavement," *Materials*, vol. 18, no. 4, Art. no. 786, 2025, doi: 10.3390/ma18040786.

[14] M. A. A. Abdelkareem, A. B. M. Eldaly, M. Kamal Ahmed Ali, I. M. Youssef, and L. Xu, "Monte Carlo sensitivity analysis of vehicle suspension energy harvesting in frequency domain," *J. Adv. Res.*, vol. 24, pp. 53–67, 2020, doi: 10.1016/j.jare.2020.02.012.

[15] J. A. Reyes-Avendaño, C. Moreno-Ramírez, C. Gijón-Rivera, H. G. Gonzalez-Hernandez, and J. L. Olazagoitia, "Can a semi-active energy harvesting shock absorber mimic a given vehicle passive suspension?," *Sensors*, vol. 21, no. 13, Art. no. 4378, 2021, doi: 10.3390/s21134378.

[16] P. C. Tesso Woafo, G. Gagliardi, A. Casavola, and F. Tedesco, "A novel multiobjective optimal LQ control strategy for energy harvesting in vehicle suspension systems," *ISA Trans.*, vol. 167, pt. B, pp. 1536–1552, 2025, doi: 10.1016/j.isatra.2025.09.010.

[17] K. Nguyen, M. Bryant, I.-H. Song, B. H. You, and S. Khaleghian, "The application of PVDF-based piezoelectric patches in energy harvesting from tire deformation," *Sensors*, vol. 22, no. 24, Art. no. 9995, 2022, doi: 10.3390/s22249995.

[18] G. Li *et al.*, "Triboelectric-electromagnetic hybrid wind-energy harvester with a low startup wind speed in urban self-powered sensing," *Micromachines*, vol. 14, no. 2, Art. no. 298, 2023, doi: 10.3390/mi14020298.

[19] Y. Jiang *et al.*, "Self-powered traffic lights through wind energy harvesting based on high-performance fur-brush dish triboelectric nanogenerators," *Small*, vol. 20, no. 40, Art. no. e2402661, 2024, doi: 10.1002/smll.202402661.

[20] N. T. Tag'ayev, F. Y. Ramazonova, and A. N. Tag'oyev, "Transport vositalari yordamida elektr energiyasi ishlab chiqarish qurilmasi [Device for generating electric energy by means of vehicles]," Uzbekistan Patent IAP 8475, Mar. 26, 2026.

[21] Q. Chen, C. Li, and M. Lv, "An array magnetic coupling piezoelectric and electromagnetic energy harvester for rotary excitation," *Micromachines*, vol. 14, no. 8, Art. no. 1527, 2023, doi: 10.3390/mi14081527.

[22] G. Tang *et al.*, "A non-resonant piezoelectric-electromagnetic-triboelectric hybrid energy harvester for low-frequency human motions," *Nanomaterials*, vol. 12, no. 7, Art. no. 1168, 2022, doi: 10.3390/nano12071168.